Suppression of the superconducting critical current of Nb in bilayers of Nb/SrRuO$_3$

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Abstract

In bilayers consisting of ferromagnetic and superconducting films, the ferromagnetic film in its domain state induces inhomogeneous distribution of magnetic fields in the superconducting film. When the ferromagnetic film has bubble magnetic domains in a labyrinth structure, it has been found that the pinning of the vortices increases; hence, the critical current of the superconducting film becomes larger. Here we study the effect of parallel ferromagnetic domain structure in $Nb/SrRuO_3$ on the critical current of Nb with current flowing perpendicularly to the domains and find that in this case the ferromagnetic domain structure decreases the critical current.

I. INTRODUCTION:

The critical current (I_c) in type II superconductors is limited by the pinning strength of the vortices, since the current applies force on the vortices leading to vortex motion which dissipates energy and destroys superconductivity. Different techniques for creating vortex pinning were proposed, including thickness modulation [1], columnar defects [2] and introduction of magnetic particles on the superconducting film [3, 4]. Most of those techniques were based on local suppression of the superconducting state, since it is favorable for the vortex normal core to be located in areas which are normal anyway; hence saving the condensation energy.

Recently it was proposed to pin the magnetic flux of vortices rather than their normal core [5]. This magnetic pinning can be achieved in superconductor - ferromagnet (SC/FM) multilayers. The magnetostatic interaction between magnetic flux of the vortices and magnetization of the FM layer gives rise to pinning potential across the domain structures that increases the superconducting critical current [6, 7, 8]. This method was demonstrated in systems where the FM film had bubble magnetic domains in a labyrinth structures, such as CoPt or $BaFe_{12}O_{19}$ [6, 7, 8]. On the other hand, no additional pinning force is expected in FM/SC multilayers if the vortex motion is parallel to the domain structure [6].

Here we study the influence of in-plane magnetic stripe domain structure of $SrRuO_3$ on the critical current of Nb in SC/FM bilayers with current flowing perpendicularly to the domain structure (Fig. 1). In this configuration vortices are forced to move *parallel* to the domain walls due to the action of Lorentz force [$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$]. We show that in this configuration the superconducting critical current decreases, suggesting lower vortex pinning.

II. EXPERIMENT:

SrRuO$_3$ is a 4d itinerant ferromagnet. In this experiment we use thin films of SrRuO$_3$ with Curie temperature of $\sim$ 150 K and saturated magnetic moment of $\sim$ 1.4 μ_B per ruthenium. The films have orthorhombic structure and since they are grown on slightly miscut substrate of (001) SrTiO$_3$, they grow with their c axis in the film plane and the a and b axis at 45^0 out of the plane of the film. The films have large uniaxial magnetocrystalline anisotropy field ($\sim$ 10 T) roughly along the b axis and consequently the magnetic domain structure is in form of stripes parallel to the in-plane projection of the b-axis (see Figure 1) [9]. The thickness of the domain walls is $\sim$ 3 nm and the domain wall spacing is $\sim$ 200 nm.

The large uniaxial anisotropy field combined with the much smaller self field (4πM $\sim$ 0.2 T) prevent the creation of closure domains and once the domain structure is annihilated by applying sufficiently large magnetic field (2 T) at a temperature lower than the Curie temperature, no new domains renucleate when the field is set back to zero [9].

Our measurements were done on SC/FM bilayers consisting of an epitaxial thin film of SrRuO$_3$ (900 Å) grown by reactive electron beam coevaporation [10] with properties as described above and a thin policrystalline film of Nb (600 Å) grown by sputtering. The layers of SrRuO$_3$ and Nb were separated with a buffer layer of Cu (20 Å) to avoid oxygen migration.

To elucidate the effect of the domain structure in SrRuO$_3$ on the critical current of Nb, I-V curves at zero applied field were measured with the SrRuO$_3$ film uniformly magnetized or with the SrRuO$_3$ film in its stripe domain structure. When SrRuO$_3$ is fully magnetized there is practically no induced field on the Nb film due to demagnetization, so comparing the critical current in the two cases yields the effect of the field due to the domain structure.
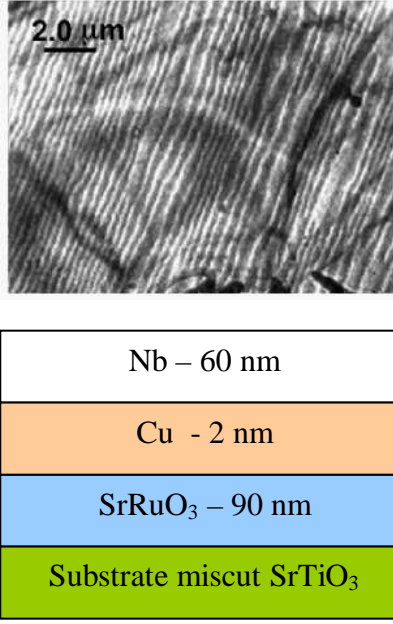
FIG. 1: Top: Image from [9] of domain walls in $SrRuO_3$ at 100 K with Lorentz mode TEM. Bright and dark lines image domain walls at which the electron beam diverges or converges, respectively. Bottom: FM/SC bilayer structure (with a buffer layer of Cu).

To measure the I-V curves of the Nb film with no field penetrating from the $SrRuO_3$ film, the sample was cooled from above the Curie temperature of $SrRuO_3$ ($\sim$ 150 K) in a field of 2 T down to 10 K. This prevented the formation of magnetic domains in the $SrRuO_3$ film. At 10 K the field was set to zero and the $SrRuO_3$ remained fully magnetized in a single domain state. The sample was then cooled down under the T_c of Nb (7 K) at zero field. The I-V curves were measured at different temperatures from 2 K up to the T_c of Nb. We call those measurements field cooled measurement (FC). Between every two sequential I-V measurements the sample was heated above the T_c of Nb so that each measurement started with no penetration of vortices into the Nb film. In the second type of measurements the sample was cooled from above the Curie temperature of $SrRuO_3$ at zero field to below the T_c of Nb and I-V curves were measured at the same range of temperatures. We call

those measurements zero field cooled measurement (ZFC). In those measurements magnetic domains formed inside the $SrRuO_3$ film and magnetic flux penetrated into the Nb film.

III. RESULTS AND DISCUSSION:

Figure 2 shows ZFC and FC I-V curves of $Nb/SrRuO_3$ bilayers measured at T=4.7 K. A strong suppression of I_c is observed when $SrRuO_3$ is in its domain state. The ZFC - I_c obtained at 4.7 K is $\sim$ 1.6 times smaller than FC - I_c.
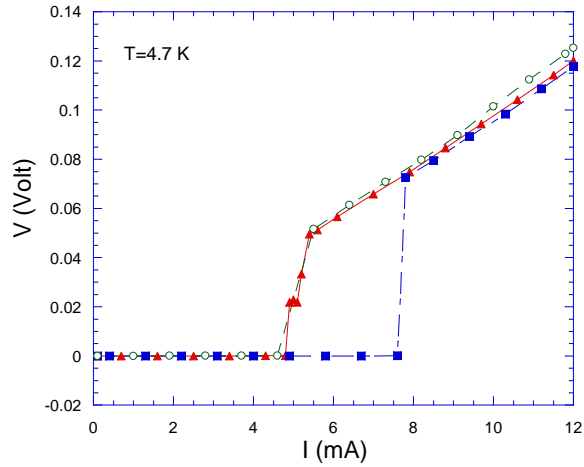

FIG. 2: Three I-V curves of a $Nb/SrRuO_3$ bilayer at T=4.7 K: (a) $SrRuO_3$ is in its domain structure (triangles); (b) $SrRuO_3$ is fully magnetized (squares); (c) $SrRuO_3$ is fully magnetized and a magnetic field of H=1600 Oe is applied along the plane of the sample (circles).

To estimate the value of the effective magnetic field induced by the magnetic domain structure of $SrRuO_3$ on the Nb film we measured I-V curve with the $SrRuO_3$ film fully magnetized and external magnetic field, **H**, applied in the plane of the sample. As it is seen in Figure 2, the effect of the domain structure of $SrRuO_3$ on the I_c of Nb is similar to that of an applied magnetic field of 1600 Oe. Such a field is consistent with our estimations based on calculations of Sonin [11] (Fig 3), who calculated the fringing field created by
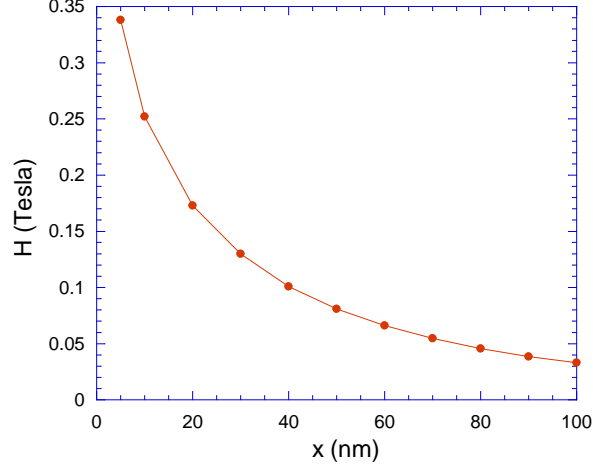
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FIG. 3: Numerical calculations of the magnetic field induced by the domain structure as a function of distance from the domain wall, x, in our SC/FM bilayers, based on the calculations in Ref. [11].

the magnetic structure at the interface between FM and SC layers in the SC/FM bilayers. Despite the difference in the field distribution in case of the field produced by the stripe domain structure and the uniform applied field, we note that the results are of the same order of magnitude.
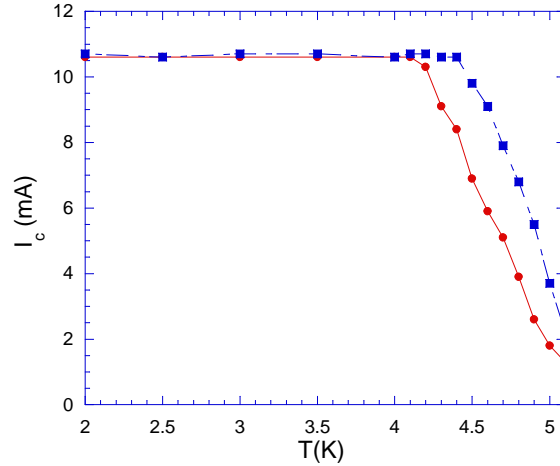

FIG. 4: I_c vs T of a Nb/SrRuO$_3$ bilayer, when SrRuO$_3$ is fully magnetized (squares) and when it is in its domain structure (circles).

Figure 4 displays the temperature dependence of the superconducting critical current with the $SrRuO_3$ film fully magnetized and with the $SrRuO_3$ film in stripe domain structure. As it appears, there is a range of temperatures, approximately between 4.2 and 5.2 K, where I_c is suppressed by the magnetic field induced by the magnetic structure of the $SrRuO_3$ film. The suppression of I_c is less clear above 5.2 K, since no sharp superconducting - normal phase transition is observed and it is difficult to determine the difference between the values of ZFC - I_c and FC - I_c.
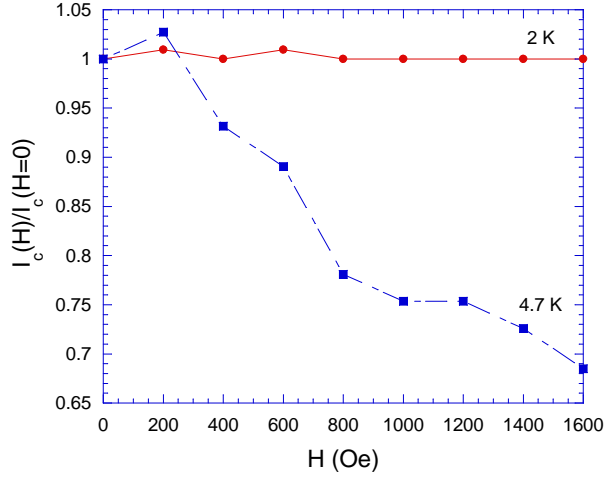

FIG. 5: I_c vs H of Nb at T=2 and 4.7 K normalized to the values of I_c at H=0.

In the temperature range with sharp superconductivity to normal transition, the ZFC - I_c and FC - I_c are practically identical at low temperatures, while above 4.2 K there is a clear difference between their values. These behavior can be understood from the field dependence of I_c at various temperatures [see Fig. 5]. The I-V curves, measured at T=2 and 4.7 K, show the dependence of I_c on the magnetic field, **H**, applied along the plane of the sample, when the $SrRuO_3$ film is fully magnetized. At low temperatures (T=2 K) no variations in I_c are observed in the field range that domain walls can produce, while significant variations are observed at 4.7 K for the same field range.

IV. CONCLUSION:

We have shown that in bilayers of $Nb/SrRuO_3$ with current flowing perpendicularly to the domain walls there is a temperature range in which clear suppression of the critical current is observed.

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